Arnold Schwarzenegger
Governor

LOW-COST, ENERGY SAVING MOTOR CONTROLLER FOR RESIDENTIAL AND INDUSTRIAL BUILDINGS

INDEPENDENT ASSESSMENT AND FINAL EISG REPORT

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Acknowledgements

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Abstract

This project addressed use of single-phase electric drive techniques for electric motors for residential and small industrial settings. With only a standard 110 V or 220 V single-phase, 60 Hz input, the goal was to build an inexpensive, 500-watt motor drive that had high efficiency and adjustable speed for load matching. Such a system is intended to replace machines in blowers, refrigerators, air conditioning units, and the like. Typical single-phase motors for these applications are 40%-50% efficient at best (estimates vary widely), under optimal conditions: at a particular speed and load. The goal here was to increase the efficiency to 70% over a range of speed and load. With widespread use, such a system would save large amounts of money and energy for California, as well as all industrialized society.

The use of small electric drives is desired by many, but cost and reliability have been major obstacles. Therefore, a $40/unit manufacturing cost (one million units/year) and 10-year mean-time-between-failure goal was specified for the total system. Under different use and comparison scenarios, with this cost the system could pay for itself in six months to two years. The resulting system nearly met the efficiency target (with known correctable deficiencies) and likely meets the production cost and reliability goals.

The conclusion is that the feasibility of the goals was established, but a fully manufacturable product would take another one to two years of development. In course, we had several ideas that would significantly reduce cost and complexity, but would require more research to evaluate.

Executive Summary

1. Introduction

This project aimed to produce affordable, near drop-in replacements for standard single-phase motors, such as those common in refrigerators, air conditioners, and other household or industrial settings, with electronically-controlled motors (that is, an electric drive). The devices would be much more efficient and versatile. The efficiency of the motor reduces the energy cost of the motor itself. The versatility, namely speed control, reduces the energy cost of the load. Low cost and high reliability were priorities to address market penetration.

The project was inspired by the 2003 Future Energy Challenge proposed by the Department of Energy. The Challenge lay out some motivation and specifications for the electric drives. The motivation is to greatly reduce energy consumption of residential and small industrial motor applications. The specifications were tailored to provide a single benchmark goal, as each application would have slightly different criterion.

Our project is differentiated from other work in single-phase powered small machines in that we simultaneously attacked motor and electronic design. Prior work mainly focuses on electronic design based on existing motor designs, under the premise that motors are old technology with little improvement to be had. However, with electronic control many old issues with motor design are removed, and the machine can be made cheaper or more efficient or both.

2. Project Objectives

The project objective was to build a single-phase powered electric motor that

- has 500 watt (approximately air conditioning or refrigeration) output power
- has 70% efficiency over a speed range of 150 to 1500 rpm
- has a unit cost of $40, assuming one million units per year

Such a technology would be significantly more efficient than the standard single-phase motors used today, but at about $30 more cost per unit. The cost premium would be made up in about six months to two years, depending on use. This is conservative since it does not include the improved efficiency of the load that would presumably occur from the load matching (i.e. speed control) capability that has been added.

3. Project Outcomes

The following contributions were made

- built and tested a prototype that met above objectives, except slightly less than 70% efficient
- identified design flaws that reduce the efficiency, and have likely viable solutions ready for future prototypes
- identified a few areas where cost could be further reduced

4. Conclusions

This project showed that meeting the above objectives is viable. However, it was not easy – we assembled a team of two faculty, one engineer, and approximately twelve students (many working for free) in order to achieve the stated results. In fact, we had several ideas for further improvement that we did not have time to implement.

The results show that the standard single-phase motors currently in widespread use should soon be replaced with the electronically-controlled motors, perhaps similar to that which we proposed. A key advance is that the cost of the motor must be reduced to partially make up for the cost premium of adding electronics. This meant we must redesign the motor with the precept that electronic control would be used. However, product development financed by the manufacturer would be appropriate for market viability, but fin. Further cost increases and significant field testing would be expected from major drives manufacturers prior to adopting the technology.

Our suggestion is that even more aggressive specification (perhaps only $20/unit) of the system would dramatically improve the market penetration. A common problem with energy-efficient appliances is cost – that is, certified units are considered "premium" as opposed to "standard". Therefore, a truly successful product would actually be cheaper than the standard solution of today. Alternatively, government standards could be implemented.

5. Recommendations

Our recommendations are

- redo the project with a more aggressive cost specification
- relax some specifications so that achieving lower cost is more viable
- fully investigate other ideas that there was not time or funding for
- begin working with small-motor manufacturers to determine more precisely what specifications would be highest interest

6. Public Benefits to California

This project benefited Californians by

- advancing the state-of-the-art in small-motor design, which if implemented in practice will save much energy and money.
- identifying key issues and ideas with meeting project specifications that should be immediately investigated, which if implemented would further reduce energy consumption for Californians

Introduction

Billions of dollars and kilowatt-hours are wasted every year due to unnecessarily low efficiency of standard, small single-phase motors commonly used in residential and industrial settings. These machines power fans, appliances, compressors, blowers, and the like and typically achieve less than forty to fifty percent efficiency (and that is under optimal conditions). Thus this project addresses the PIER program's building end-use efficiency thrust. The power loss occurs for several reasons

- single-phase motors are inherently difficult to build for efficiency
- they are generally induction machines, that when driven straight off the power line must be heavily loaded for their peak efficiency. At light loads, which is common, efficiency is terrible.
- Their power factor (a relationship between useful power delivered against the current required to deliver it) is low, resulting in extra loss in power lines and larger cabling

In addition, they offer no method for continuous speed control, which means that valves, gears and other lossy mechanisms must be used to accommodate the load. With variable speed, load matching could be used, further increasing *system* efficiency on top of motor efficiency. The alternative is to use and electronically-controlled motor drive (or just "drive" for short). A drive solves all of the above problems. A naturally efficient three-phase motor can be used instead, since the drive can convert single phase to three phase. Speed control is readily available, and the power factor can be set as we will.

Why, then are drives not often used in small-motor applications? Of course the answer is "cost." It is the purchase cost and not the life cycle or environmental cost, however. Standard single-phase motors have been in production for decades and are just about as cheap as they can be. Any addition to the cost, such as adding electronic control, ultimately increases cost to the end user. Therefore, electronic control must be added such that the advantages outweigh the cost premium.

To address this well known problem, the Department of Energy sponsored the 2003 Future Energy Challenge [1]. The Challenge offered cash prizes to student teams to redesign the single-phase powered motor system for residential applications. The goal was to dramatically improve efficiency at a sufficiently small cost premium. The panel of experts concluded that a system with 500 W output, variable speed, high power factor, and greater than 70% efficiency could be marketable if the manufacturing cost were below $40/unit for million unit per year production.

The University of Illinois sought Commission sponsorship under the EISG program to meet this Challenge. An additional $10,000 was obtained from the Grainger Center for Electric Machinery and Electromechanics, and $5,000 from the National Science Foundation. Emerson Motor Co. donated some materials and gave some engineering advice. The result was a substantial effort of two faculty members, one research engineer, and approximately twelve students (many working as volunteers or for course credit, all part-time) over one year that met all goals, except slightly lower efficiency. Further, key weaknesses in our first-year approach were very clear and have ready solutions that will either improve performance or further reduce cost. Some of our results were summarized in the technical paper [2].

The report is organized as follows. First, we fully specify the project objectives. Then, we describe our approach to meeting those objectives on a task-by-task basis. Next, the project outcomes are discussed relative to the objectives and finally, future directions are suggested.

Project Objectives

The project objectives were the key specifications set forth by the 2003 Future Energy Challenge. They were:

1) Build a motor system with 500 W output that runs from standard household electricity
2) Achieve 70% system efficiency with a 10:1 speed range
3) Achieve a unit manufacturing cost less than $40, assuming one million units per year

There are many more specifications set forth. Most in regard to minor details such as mounting dimensions, safety issues, etc. Items 1) to 3) embody the main challenge. Not mentioned in 1) to 3) is to achieve a power factor greater the 0.8 at full load, which was specified by the Challenge. Therefore, our system was a over-designed relative to 1) to 3). The power factor correction stage could be easily eliminated to reduce cost, at loss of high power factor. Power factor in and of itself does not provide a selling feature since most users will not see obvious benefits to having high power factor. However, low power factor results in more expensive wiring and can make efficiency easier to achieve in the drive front-end converter.

These objectives provide benchmarks for designs. Obviously, not every residential application uses the same power or benefits greatly from high efficiency (e.g. a garbage disposal). However, these objectives are a fair compromise to inspire breakthroughs in the general problem of small-motor redesign.

Project Approach

The project was approached in five tasks, listed in Table I below. The percentage complete of each task is listed as well.

Task	% Complete
1: Design integrated motor and drive system	100
2: Build 500 W slotless induction motor	75
3: Build 500 W electronic drive	100
4: Perform necessary online tests	100
5: Estimate cost of proposed system	100

Task 1: Design and integrated motor and drive system

The design consisted of two major, but interrelated, parts: the motor and the electronic control (drive) system. Considerable planning during the early months of the project went into system architecture and choice of motor topology. Given the high production quantity, it was deemed preferable to go with a simpler design that relied on readily available parts, where we focus on getting the cost down while preserving functionality. The alternative approach was to go with nonstandard system components that may have higher performance potential. This would be more typical for lower quantity runs where more risk can be tolerated.

The overall system is shown in Fig. 1. It consists first of a front-end power factor correction (PFC) plus rectifier stage which produces 200 V dc while imposing near unity power factor on the input. The PFC is followed by an inverter, which delivers variable frequency, variable magnitude ac voltage to the motor, which is a three-phase induction motor. The inverter is controlled by a digital signal processor (DSP) board.

A key component of the system is the motor. The cheapest and easiest to build motors are induction motors. The vast majority of motors used for the proposed application are single-phase induction motors. We opted for a three-phase design, which is possible to implement due to electronic control. The three-phase design takes almost full advantage of the material used in the motor- far better than single- or two-phase designs. More phases only improve material utilization incrementally, at higher cost of construction and electronic control.

Ordinary line-start induction motors are designed with compromises due to their

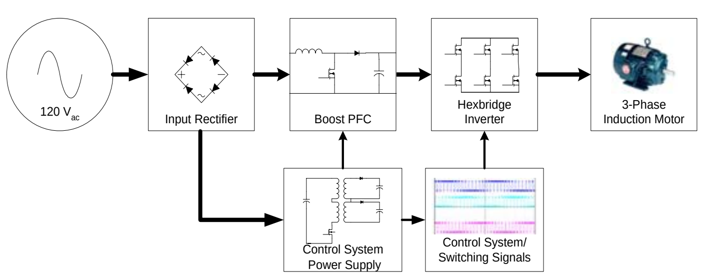

Figure 1. System Architecture.

requirement of starting from stall and running under load from a fixed frequency, fixed voltage source. With electronic control, neither the voltage nor frequency is fixed, meaning some design compromises can be eliminated. For example, induction machines have aluminum bars in the rotor that must be relatively small for starting but large for high efficiency in line-start machines. With electronic control, we can make large, efficient bars without sacrificing starting capability.

The motor was designed using a mix of commercial software and newly invented techniques. The software analyzed the electrical properties of a proposed motor design and yielded a figure of merit relating to the quality of design. A Monte-Carlo based technique for searching through a large number of design options was used to select the best design. The technique is fully described in [3]. The technique focused on rotor bar design, while using standard design options for the stator. In retrospect, a simultaneous optimization of stator and rotor would have probably produced a better motor design. However, the efficiency goal for the motor (> 70%) was met (discussed below).

The rotor and stator design for the new motor is shown in Fig. 2. The bars are much larger than is typical for a 500 W motor. This increased the efficiency at full load, but yields a lower magnetizing inductance and higher slip (the decrease in speed that comes with load). Due to the electronic control, it is possible compensate for high slip and thus we stayed with the design.

The drive electronics consisted of three main parts: the power factor correction (PFC) stage, the inverter stage, and the control stage. The PFC is a circuit that converts the 120 V, 60 Hz ac source to 200 V, dc. It also shapes the current coming from the source to be nearly sinusoidal. This yields high power factor, which means that as little current as possible is being drawn from the source for a given motor power output. Although our proposal did not address PFC, we implemented it for the Future Energy Challenge project according to the Challenge's specifications, which called for 0.8 power factor. When writing the proposal, we thought achieving 0.8 power factor could be done with simple passive components, and did not see a problem with implementing it inexpensively. However, it turned out that we could barely reach 0.8 with passive components and it was a relatively expensive design. Thus, we turned to an active design which achieved greater than 0.95.

The PFC circuit consists of a simple four-diode rectifier followed by a boost converter circuit [4]. The rectifier produces a dc voltage of about 110 V. The boost converter steps the

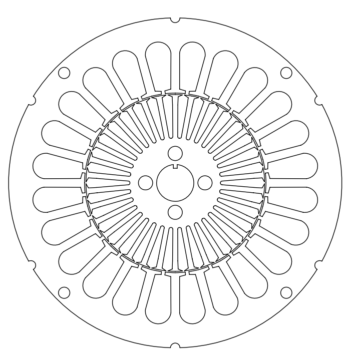

Figure 2. Rotor and Stator Laminations

voltage up to 200 V, while simultaneously shaping the input current for high power factor. We chose 200 V for a couple of reasons. First, it was a relatively small step (< 2:1) and therefore had high efficiency and low switch stress. Second, it simplified the inverter stage design described below. The PFC was designed around a dedicated PFC controller chip (see Fig. 2). The PFC achieved 800 W output at 90% efficiency and 0.95 power factor. We needed 800 W, as opposed to 500 W, to account for the 70% efficiency of the motor.

The inverter stage converts the 200 V dc power to the three-phase ac power for the motor, using variable frequency and voltage magnitude. The inverter stage, which is a standard six-transistor bridge, can be found in any power electronics text. Several unconventional alternatives have lower parts count [5-7], but they either sacrifice efficiency in the motor or require parts with higher ratings, negating the cost savings by using fewer parts. (This is not to say that these alternatives cannot be used- substantially more investigation is required to see if they hold up to the standards of conventional circuits). The inverter stage is centered on the IR2130 bridge controller. This chip simplifies the design of the various gating and delay functions necessary to control the power switches.

We extensively debated what power switch type to use, IGBTs or MOSFETs. Ordinarily, IGBTs would be considered an automatic choice for motor drives, but our analysis showed that with a 200 V dc bus, MOSFETs were available that were both cheaper and more efficient. The efficiency advantage was more obvious at low power. The MOSFETs behave like small resistors, dissipating power proportional to the square of current. IGBTs dissipate power linearly with current. Thus at low power (current), the MOSFETs were much more efficient. Since we found MOSFETs that had the same efficiency as IGBTs at high power, and with lower cost, we settled on a MOSFET design.

The last stage is the control stage. This stage determined the switching action of the inverter stage; that is, to control the voltage and frequency of the three-phase motor as required by the load. Since our specifications require efficiency at high speed (power) and low speed (power), we had a problem using the usual switching strategy known as sinusoidal pulse width modulation (SPWM). SPWM forces the switches to switch at the same frequency regardless of the motor power and speed. This causes unnecessary switching losses at low speeds. Thus, we opted to use a variable switching frequency strategy known as selective harmonic elimination (SHE) [8]. SHE is an old idea, but relatively unused in variable voltage applications due to the complications with practical implementation [9]. However, our team successfully implemented SHE at all frequencies and voltage levels required by the specifications, which was a major undertaking [2].

The SHE waveforms for one particular simulated operating point are shown Fig. 3. The traces shown are the actual voltages applied to the motor. By varying the spacing and widths of the pulses, the motor's speed can be adjusted. The SHE algorithm was implemented on a digital signal processor (DSP). A DSP is a like a miniature computer that has a very specific purpose. Some debate about the use of a DSP occurred. On one side, a DSP is normally considered too expensive relative to the $40 cost target. On the other side, we realize in mass production we wouldn't use the same DSP- instead, it would be an application specific integrated circuit (ASIC) with the absolute minimum functionality needed. While impractical for a prototype design, and

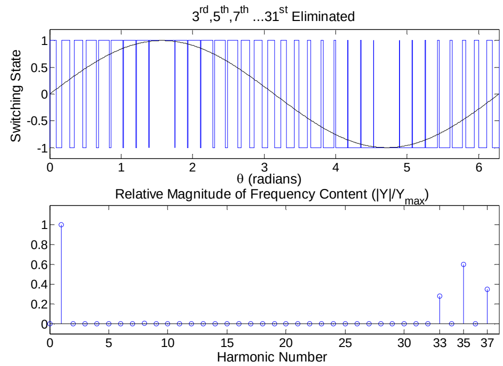

Figure 3. Simulated Switching Function and Harmonic Content

ASIC is very appropriate for one million/year quantity production. The DSP was a convenient template to build a prototype around, but certainly not a final design.

The control stage accepted a speed command signal of zero to ten volts, dc. Aside from implementing the SHE algorithm, the DSP read and interpreted the speed command. Based on the command, the pulse width and spacing of the SHE algorithm could be calculated. The frequency of the motor voltage is normally close to the motor speed. Since our motor had high slip, there is a disparity between electrical frequency and mechanical speed. The DSP compensates for this by sensing the motor current (which is correlated with load, and therefore the amount of slip) and further increasing the frequency and voltage to bring the speed up to the command.

In addition to the three main parts (control, inverter, and PFC), several ancillary parts of the design were necessary to make it whole and realistic for implementation. For example, the control chips (PFC, DSP, etc) and speed command circuitry require a low-power dc supply. For this we used a 'flyback' converter, which gave efficient conversion of the 120 VAC line to several low-power dc outputs. The flyback, while a minor part of the system, was complicated to design. Filtering for electromagnetic interference was used on the input line.

For overall packaging, we opted for a NEMA #48 frame for the motor and added a frame extension to the rear. In this extension, we packed the electronics and power plug and switch. Overall, a very clean-looking, integrated product resulted.

Task 2: Build 500 W Slotless Induction Motor

This task involves building the motor that was designed in Task 1. The 'slotless' aspect was a part of the project we never finished, but we did build a working slotted design. Thus, we ranked it only as 75% complete. Originally, we conceived a method of building stator windings using flexible printed circuit (flex PC) boards. The idea was that winding would be drawn in a layout package and printed in standard batch fabrication for circuit boards. This would conceivably be cheaper and faster than ordinary winding of motors, which is a slow and expensive process, not amenable to batch fabrication. The flex PC approach would probably require the normal slotted shape of the motor stator to be replaced by a slotless design. The slotless motor would have a harder time achieving efficiency, but originally we thought the cost savings could make up for that using other tradeoffs. After the official end of the project, we did finish building a slotless design reported [10].

At this point, we still have a student investigating the slotless, flex PC design, but we are not close to building it. We did build a normal slotted motor, with the optimized rotor design suggested in Task 1. This was a major undertaking, as we were not able to find *anyone* who could prototype an induction motor for us. In fact, close contacts at Emerson Motor Co. told us they don't prototype induction motor rotors anymore – they go straight from design to test run. One panelist at the Future Energy Challenge repeatedly expressed his impression with our ability to pull this prototype together.

The main difficulty was building the rotor, which involved pouring molten aluminum into the rotor slots. We had to fashion our own casting system and try twice before successfully casting the rotor. One rotor design did not rely on casting- the bars were inserted and connected together by screws. This did not perform well due to the poor electrical contacts associated with screwing the bars to the outer ring.

After building the stator and housing the whole assembly, we had spent about eight months just trying to put together the design we conceived, which obviously didn't allow time for iteration on a one-year grant. However, now we know how to do this more quickly, and future iterations will not be so time-consuming.

Task 3: Build a 500 W Electronic Drive

This task involved first 'breadboarding' the components of the drive, testing, and then refining the design repeatedly. Once satisfied with the design, we moved the drive to permanent printed circuit boards. Building the drive also involved programming of the DSP circuit, which was a major difficulty for us. One reason was some inexperience with DSP on the part of the programmer. Another reason was the implementation of the SHE with variable magnitude and frequency, which we believe may have been the first such rendering (in fact, this was a one-year project in and of itself!).

Task 4: Perform Necessary Online Tests

Once the motor and drive was assembled, the complete system was held up against the goals set forth in the objectives. Each subcomponent was thoroughly tested prior to full assembly of the system. As is usual, the total system implementation is more complicated than just connecting the individual parts. Therefore, an additional debugging stage was necessary to make all components work together (the main problem was noise from each subsystem interacting with others).

Once assembled and working, the motor drive was mounted to a dynamometer and tested for efficiency and speed control at various load torques, according to the Objectives.

Task 5: Estimate Cost of Proposed System

Estimating cost for one million unit per year production is in itself a major undertaking for even a professional contracting firm. However, quantities of 1,000 or 10,000 supply have readily available cost information. Our approach for cost estimation then relied on using cost figures for medium quantity (10,000) and extrapolating to one million. It is acknowledged that this extrapolation does not take into effect many factors that come into play with high quantity production (special deals, supply shortages, bonuses for using the same manufacturer for multiple parts, etc).

Project Outcomes

Task 1: Design and integrated motor and drive system

We successfully designed the integrated motor drive system. Some key outcomes were

- development of a induction motor rotor optimization technique
- development of a real time selective harmonic elimination technique
- identification of the hardest specifications to meet, thereby identifying tradeoffs that should be made in future specifications
- several concepts for different, perhaps improved, designs for future research

Task 2: Build 500 W slotless induction motor

We built a 500 W motor, but more of the conventional slotted kind with an optimized rotor. After the project officially ended, we did finish building a slotless, printed-circuit-winding motor, reported in [10]. Some key outcomes were:

- developed a technique to prototype induction motor rotors in a small lab setting (although this may seem trite, we found that even major motor manufacturers do not conduct induction motor prototyping, including Emerson Motor Co., who worked with us on the project)
- determined that an optimized (with respect to efficiency over a wide range of speed) rotor is better than nonoptimized, but the stator should be considered simultaneously

The rotor assembly as built is shown in Fig. 4 and the stator assembly is shown in Fig. 5.

Task 3: Build 500 W electric drive.

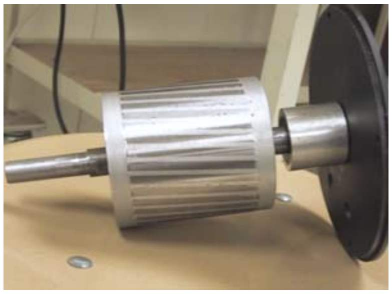

Figure 4. Rotor Assembly

Figure 51. Stator Assembly

We built a very successful drive circuit (which was actually capable of at least 800 W – to account for 70% or worse efficiency in the motor). Outcomes were

- development of novel DSP code to implement real-time, variable frequency and magnitude selective harmonic elimination
- identified several tradeoffs that could be used for future work

The PFC and inverter boards are shown in Figs. 6 and 7, respectively.

Task 4: Perform necessary online tests

We perform full system testing to determine success of design and construction of the system. Some outcomes were

- a total system that nearly met the performance specifications
- a rapid testing system for checking performance over wide range of speed and torque

Tests of each the PFC, inverter, and motor were accomplished. The correct function of each circuit was first established, and then efficency was determined.

Figure 6. Active PFC Boost Circuit

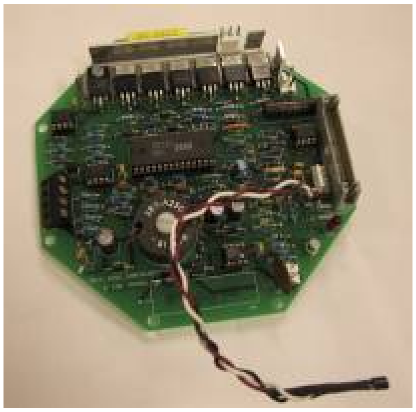

Figure 7. Inverter and Power Supply Board

Fig. 8 shows the dc voltage output of the PFC circuit (purple), the current at the input of the PFC (from the rectifier, teal), and the voltage output of the rectifier (blue). The current is nearly the absolute value of a sine wave, as desired. The measured power factor was 0.95, which is nearly the ideal value of 1. The output voltage is 200 V dc with only minor ripple. This test was conducted at 800 W.

The efficiency of the PFC stage was measured and shown versus different power levels in Fig. 9. Good efficiency occurs throughout (>90%), but it is best at low power and worst at high power. This is due to use of a MOSFET for a power switch, which has loss that significantly increases as the current (power) output increases. Higher efficiency is possible by using a more expensive MOSFET, but of course that is not a good tradeoff.

The inverter stage was tested for efficiency versus load as well. The results are shown in Fig. 10. It can be seen that the inverter is very (97%) efficient across the whole range. Additional efficiency would be hard to obtain and probably not cost effective or important. One reason for such high efficiency was the use of selective harmonic elimination, which has very

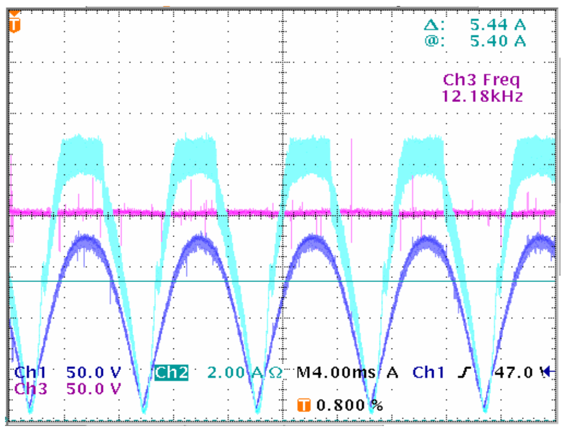

Figure 8. Active PFC Voltage and Current at 800 W loading

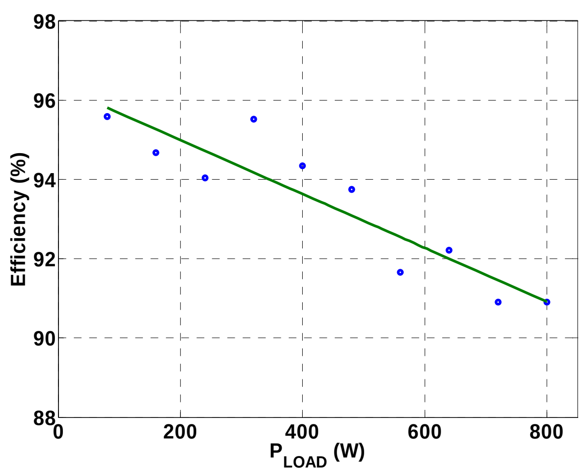

Figure 9. Active PFC Boost Circuit Efficiency

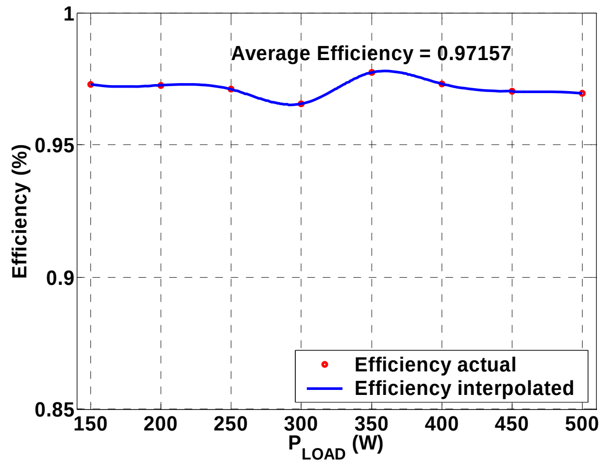

Figure 10. Inverter Efficiency at Rated Speed (1500 R.P.M.)

low switching losses.

The motor was tested for efficiency at 1500 rpm for various load torque. This result is shown in Fig. 11. The specification called for system efficiency over a 10:1 range of greater than 70%. In Fig. 11, we see that over most of the range, the machine is greater than 70% efficient. At very light loads, the efficiency drops to about 55%. This was to be expected since light load efficiency of any motor- especially induction machines is hard to achieve without excessive cost (the approach would be to make a much larger motor, one capable of more than 500 W, which is probably not a desirable trade). Thus, the motor alone contributes to most of the efficiency loss. Combining this with the losses in the electronics, we only achieve better than 70% efficiency over a narrower range (200 W to 500 W) and not all the way down to 50 W.

End-to-end efficiency can be found from multiplying the decimal (not percent) efficiencies of all thee plots of Figs. 9-11. When we conducted an end-to-end measurement, we obtained lower efficiency than we should have (Fig. 12 – pay particular attention to the 1500 rpm curve, which was the benchmark). The problem is definitely in the DSP control of the motor. While the DSP control works fine in producing commanded gating signals, our slip

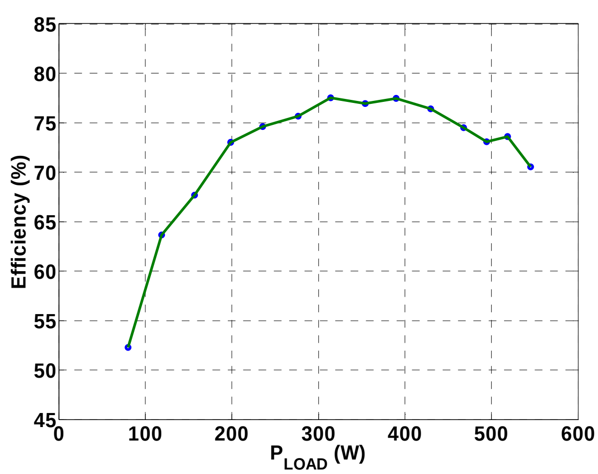

Figure 12. Induction Motor Efficiency at 1500 R.P.M.

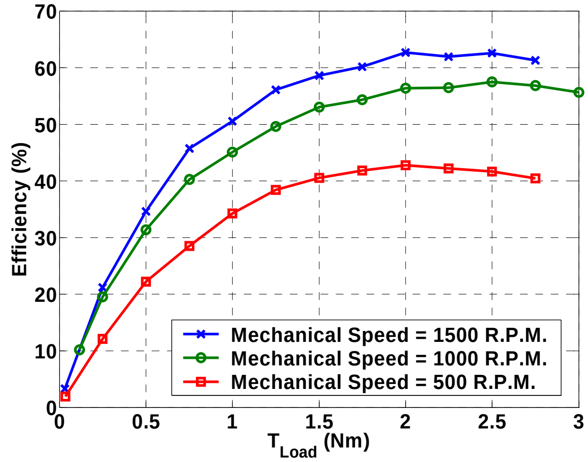

Figure 12. Efficiency at Various Operating Speeds for Complete System

compensation algorithm did not quite maximize motor efficiency. That is, the algorithm was required to adjust motor voltage and frequency to find the best combination for a given speed command. Our algorithm approximately achieved this, but the main issue was that the motor had very high slip (ordinary motors with high efficiency have very small slip).

Early on, we decided to go with large-slip motor. This reduced the *peak* efficiency but extended the high efficiency range over the whole useful range. It was necessary to do this given the specification of high efficiency at light and heavy load. That is, it does us no good to be 90% efficient at 500 W if only 20% efficient at 100 W. The large slip forced the DSP to make larger adjustments to the frequency command, meaning it was more sensitive to programming. Given more time (perhaps one or two months), our team feels we could have improved the algorithm to automatically achieve nearly the best efficiency. However, we also feel that several other changes should be made first.

Thus, the system is *capable* of meeting specifications over a large range (and nearly the whole range). This is proven through Figs. 9-11. Fine tuning of the control algorithm (which amounts to code revisions- not hardware changes) would result in better realization of this capability.

Task 5: Estimate cost of proposed system

We estimated the cost of the proposed system for 10,000 quantity, and extrapolated to 1,000,000 quantity (which is highly approximate, but the best that can be expected under the circumstances). Some outcomes were

- a system design that appears capable of <$40/unit construction
- identification of the highest cost items and how they can be traded off by slightly loosening some specifications

The cost was itemized as shown in Table 1 for both 10,000 and 1,000,000 unit (extrapolated) designs. The cost for low quanity is about $103, only 2.5 times the target. Increase the production by a factor 100 (up to 1 million) could easily push the cost down by a factor of 2.5.

Table 1. Production Cost

Subsystem	10,000 Unit	Million Unit
PFC	$31.57	$12.32
Inverter	$11.18	$6.84
Flyback	$4.33	$1.54
Control	$24.95	$3.50
Motor	$24.56	$10.17
Misc.	$7.19	$3.39
Total	$103.77	$37.76

Of course, manufacturers will not normally quote high quantities to academic researchers, as they know this information would be proprietary and the researchers are asking for information only- without direct intent to build.

The 1,000,000 quantities were based on extrapolations of quotes of several low quantities up through 10,000. The extrapolation is from quotes for lower quantity orders (1, 10, 100, 10,000 etc.). Many factors come into play as quantity is increased that cause extrapolation based on distributor quotes to be questionable. However, those factors would mainly involve dealing directly with chip or component manufacturers likely resulting in better deals than can be obtained through distributors. Furthermore, regular customers of certain manufacturers can bargain more effectively due to involvement in other projects, making a precise quote impossible to know. Therefore, it is reasonable to think that the 1,000,000 unit cost target can be met, yet our industry contacts emphasize the above points – cost computation is a complicated and unpredictable venture in high quantity.

Another factor in the cost was the PFC circuit. Our drive achieved 0.95 power factor, when only 0.8 was called for by the Future Energy Challenge. This strongly suggests a tradeoff can be made to further reduce cost. Our proposal to EISG program didn't specify power factor, thus, in the strict sense of evaluating this work against what was proposed, the cost would be even lower. However, the team believe high power factor is a highly desirable trait and should be a specification of future drives.

Conclusions

This project investigated the feasibility of building an efficient, low-cost, electronically controlled motor that is powered only from a single-phase residential supply. Experimental results confirmed that efficiency of each individual piece of the system was satisfactory (or nearly so in case of the motor), but end-to-end efficiency was lower than it could be due to unsatisfactory slip compensation. The target price of production was met according to estimates made.

We feel the project showed that making the drive with proposed specifications is feasible; however, several tradeoffs can be made to make it more feasible, as discussed in the recommendations. Furthermore, there may be several better ideas for further reducing cost or improving performance in future investigation.

Recommendations

The team recommends further study of this problem, but with more aggressive cost targets, perhaps in exchange for lower performance. Realistically, the best way to bring this to market is not only to show better performance, but *lower* cost than the standard single-phase motors. A “more-for-more” approach is not as likely to attract as much interest as a “more-for-less” approach (a well-known historical challenge).

A major cost issue was the requirement of high power factor (> 0.8). High power factor is important for reducing current on transmission lines for given real power output, as is efficiency. Therefore, a better specification would be to trade off efficiency and power factor to optimize cost. Power factor of 0.8 is an awkward goal- not quite achievable with passive components, but easily achievable (nearly 1) with active control. This suggests a slightly relaxed power factor (so that a passive solution can be used) could result more cost headroom to improve other parts of the drive. Some readers will justifiably believe that high power factor is too important of a feature to ignore, whereas others, also justifiably, will believe that power factor is a feature that is difficult to sell.

Another issue was the use of an induction motor. Other motor topologies may be slightly more expensive, but more efficient. The main alternative is the permanent-magnet synchronous machine. Usually, permanent magnets are considered very expensive (at least the rare-earth kind that would likely be required here), and a low-cost permanent-magnet motor would be considered a contradiction in terms. However, it is conceivable that the increased efficiency can be traded off with other costs of the system including weight, volume, and cost of the electronics. Cost-effective high-speed operation (if necessary) is an issue for permanent-magnet motors that would need to be overcome. Thus the recommendation is to consider other motor topologies.

Another recommendation is to try to cut out some of the support circuitry. The flyback converter, for instance, was an efficient way to power the circuit peripherals. However, it was a major and consistent problem in our design. It was the most regular cause of failure and was a significant cost. A simpler, but less efficient design, such as an ordinary linear regulator could be used instead. This would sacrifice efficiency, but help reliability and shorten design time considerably.

Yet another recommendation would be to focus more on the control for maximizing efficiency. A disproportionate amount of time was spent on developing the real-time selective harmonic elimination code for the DSP, leaving little time for optimization. Several standard DSP’s have built-in modulators that would not have as low of loss as the harmonic elimination, but they would take no time to develop. Thus future work can use the harmonic elimination code developed, but should focus more on what to do with that code, than with writing it elegantly. Luckily, this task need only be accomplished once provided the code can be ported to future systems.

The team generated several other, perhaps more radical ideas, in course. However, there was not enough time to begin to implement them. These suggestions remain proprietary for the time being, but are a subject of ongoing work. So, the last recommendation is to consider investigating some more unusual concepts that have high-risk, high reward.

Benefit to California

California has its share of electricity users (air conditioning, refrigeration, etc.) that can benefit from improved efficiency. The proposed work not only improves efficiency of the motor itself, but through load matching improves efficiency of the mechanical process therein. The proposed concepts are more likely to be implemented in environmentally sensitive states such as California, particularly if more aggressive energy efficiency laws are enacted on building end-use components.

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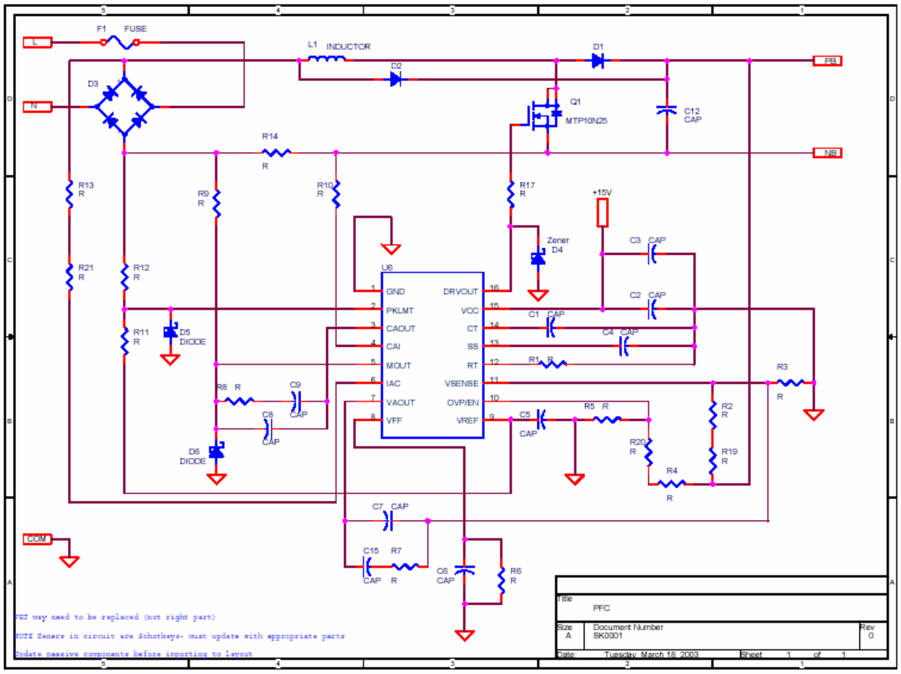
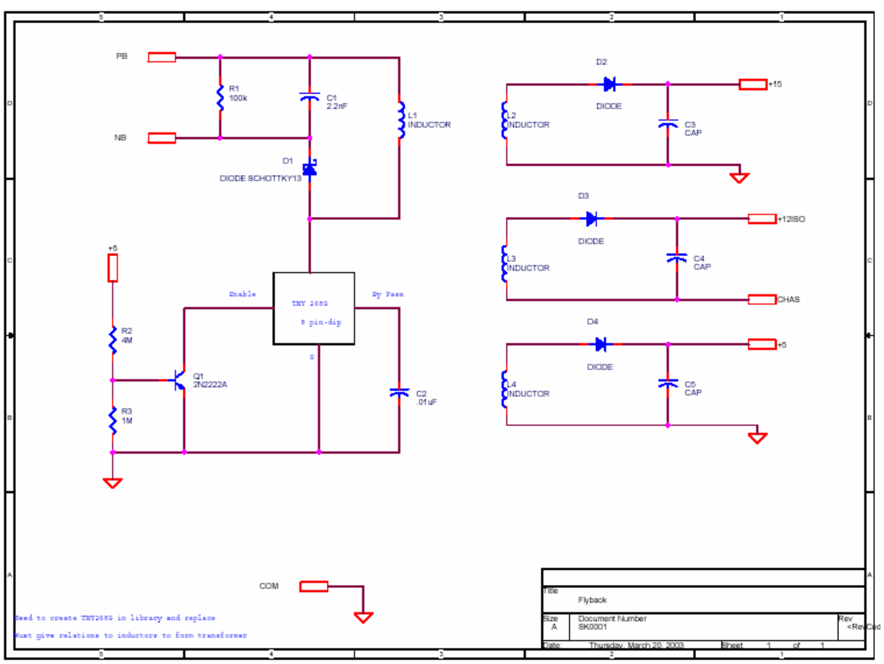
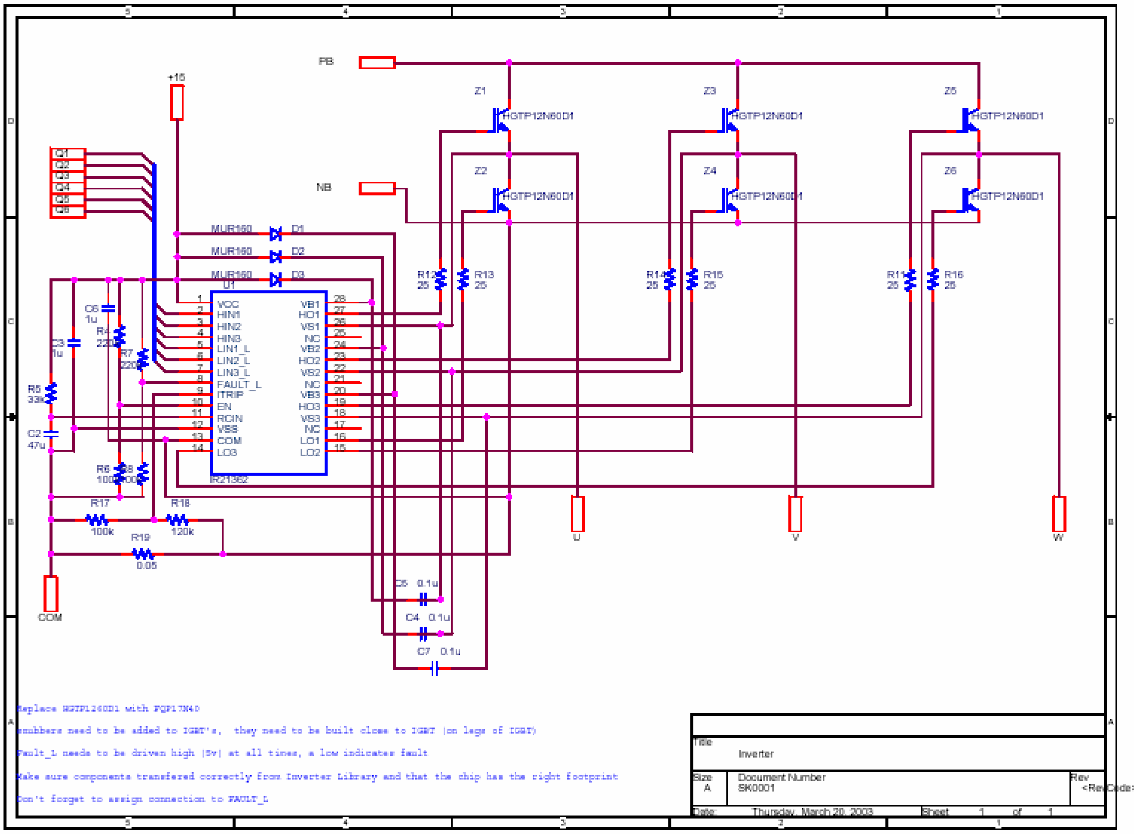
Appendix- Schematics of Electronic Drive



Power Factor Correction Circuit



Power Supply Circuit



Inverter and Gate Drive Circuit

Attachment A – Grantee Report

LOW-COST, ENERGY SAVING MOTOR CONTROLLER FOR RESIDENTIAL AND INDUSTRIAL BUILDINGS

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